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Parking the power: Strategies and physical limitations for bulk energy storage in supply–demand matching on a grid whose input power is provided by intermittent sources

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ABSTRACT

It is shown that, in a sustainable energy future, energy for the electricity grid will probably be derived largely from the renewable sources of wind and solar radiation. Because both are intermittent, any infinite busbar grid supplying a metropolitan area must necessarily be buffered from these intermittencies by massive energy storage on the gigawatt-day level. It is then demonstrated that, under presently foreseeable scientific capabilities, only underground pumped hydro and advanced adiabatic compressed air energy storage appear capable of meeting anticipated technological and economic constraints. Neither has ever been constructed and tested; but even so it is predicted that underground pumped hydro ultimately will prove to be superior.

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Nomenclature

C	the energy capacity of a reservoir (J)
$\mathcal{D}$	energy density $\mathcal{C}/\mathcal{V}$ of a charged reservoir (J m^{-3})
h	the Planck constant 6.6256×10^{-34} (J s)
p	power, in particular electrical power flowing along a transmission pathway (W)
$\mathcal{P}_{max}$	the maximum recommended discharge rate of an energy reservoir (W)
t	time (s)
t_c	The crossover time between a biphasic cycle of charging (or discharging) and discharging (or charging) (s)
T	The length of the period over which $p(t)$ is averaged to obtain η (s)
$\mathcal{V}$	volume of an energy reservoir (m^3)

Greek letters

δ	The minimum recommended drawdown rate of an energy storage reservoir (s^{-1})
η	efficiency, in particular the cycle efficiency of and energy storage system
ν	the frequency of a monochromatic radiation (Hz)
τ	a time characteristic of the interval needed for $p(t)$ to approach steady state following a deliver-power command (s)

1. Introduction

Electrification of the United States of America was proclaimed that nation's single most significant technological advance during the 20th century [1]; and it was a key enabler for most of the other top 20 (cf. Fig. 1). The skeleton supporting any country's electrification is its grid (that is, the reticulate high-voltage transmission network) which carries reliable energy to local intermediate-voltage distribution lines that in turn deliver it to low-voltage neighborhood lines. Undergirding this entire system (and much of electric power engineering) is the simplifying hypothesis that a grid is an "infinite busbar" which maintains a fixed voltage and fixed waveform while supplying as much or as little energy as required. When consumer demand grossly exceeds generating capacity, the grid voltage sags and brownout results. When consumer demand drops significantly below generating capacity, the suppliers of that capacity are forced to down-regulate it, as for example by temporarily taking generators off line or by reducing generator output. This interplay between supply and demand plays out daily in energy markets across the United States with a sinuous quasi-periodic demand curve that rises from a low point just before dawn to a peak in the afternoon and then tapers off.[1] This variation in demand can be satisfied only because (i) the grid can withstand "small" fluctuations of demand on the few-second time scale without seriously compromising power quality [2,3], (ii) electromechanical storage devices and regulatory constraints can take up larger short-term disturbances and (iii) predictable diurnal variations can be handled by hydrocarbon-based thermal generation. In the long term, hydrocarbon-based generation cannot continue because our supply of fossil hydrocarbons which steadily powers thermal generation is both finite and undergoing rapid depletion [4,5].

Even if the greenhouse gas constraint were to be resolved, whether by ignoring it and accepting the environmental consequences (e.g., [6]) or by carbon sequestration [7–10], we ultimately shall exhaust our dowry of fossil hydrocarbons (e.g., [4]) and shall have to look for other means of powering not only the electric grid but everything else as well.

2. Sources of sustainable energy

There are two sustainable primary sources of harvestable energy which impact the earth: gravitational and nuclear; they and their derivatives are displayed and organized in Fig. 2. Gravitational arises from the Earth–Moon interaction, is manifested in the tides which can be harnessed (cf. [11,12]), but which are predictably intermittent and will require energy storage to interface smoothly with the electric grid. Nuclear processes may become manifest in three basic ways:

(1) Fusion driven solar heat radiation which, each day on average, deposits a few hundred watts per square-meter of near-visible electromagnetic radiation on the surface of the Earth and drives not only photosynthesis but also both climate (with its winds, rains, and waves) and all direct human photon capture and conversion (whether photovoltaic or high temperature thermal[2] or low temperature thermal) [13,14].
(2) Nuclear decay deep within the planetary interior which drives geothermal processes.
(3) Human-mediated nuclear processes such as controlled fission or (potentially) fusion.

2.1. Heat radiation from nuclear fusion reactions

2.1.1. Solar heat radiation: Natural photochemistry (biomass)

The future prospects for meeting humanity's energy desires with photosynthesis-derived biomass are equivocal [15–19]; indeed, humans already appropriate approximately one-quarter of net primary productivity of the planet's land surface [20]. In particular, the grid electricity consumed by the United States cannot sustainably be supplied by its foreseeable annual production of biomass; and besides, any land which can be spared from the needful production of edible plants, edible animals, and structural materials (e.g., timber or cotton) might better be devoted to the production of petrochemical feedstocks for non-energy uses (cf. [21]). Also on the down side, conversion of light to biomass presently has an efficiency[3]

[1] Supporting data for this assertion do exist, but are accessed for the first time only with some labor. For example, selecting http://hydrogen.its.ucdavis.edu/people/obart/index_html, accessing the first paper under "Research Docket" and going to Fig. 1.2 gives illustrative data for the Solano (California) Municipal Utility District. To obtain raw tabular data for a utility of your choice, it is necessary to access the site of the Federal Energy Regulatory Commission http://www.ferc.gov/docs-filing/eforms/form-714/view-soft.asp, download Form 714 Data Download, perform a Form 714 Viewer application, then execute a Form 714 Data Download, perform a Form 714 Viewer application, and select Part III – Schedule 2; this form then provides, at poor visual resolution, hour by hour utility demand throughout the calendar year selected. The upshot of this is that the claim of a "sinuous quasi-periodic demand curve ..." is sustained.

[2] High, medium, and low temperature here refer to the working temperature of a fluid into which the photon energy has been transferred. In one system, the two boundary regions are set based upon the tasks for which the heated fluid will be employed as $T_{LM} \doteq 100\,^{\circ}$C and $T_{MH} \doteq 400\,^{\circ}$C ([13], Section 2.2.3; [14]). Here our specialized interest is the efficiency of conversion from radiation to sensible heat to mechanical energy and thence to electrical energy; we therefore set $T_{LM} \doteq 102\,^{\circ}$C (Carnot efficiency 20%) and $T_{MH} \doteq 394\,^{\circ}$C (Carnot efficiency 50%), where the "dead state" of the system has arbitrarily been set to 300 K.

[3] Within discussions of sustainability, the precise meaning of energy "efficiency" is sometimes neither rigorously defined nor context-independent (e.g., [18,22]). For the purposes of evaluating the techniques of grid energy storage, we shall endeavor to use it in the sense of a limit over time of the ratio (total energy recovered from a reservoir)/(total energy delivered to that reservoir); over a single period of charging and discharging, it is frequently called "cycle efficiency". This is discussed further in connection with Eq. (2) below.

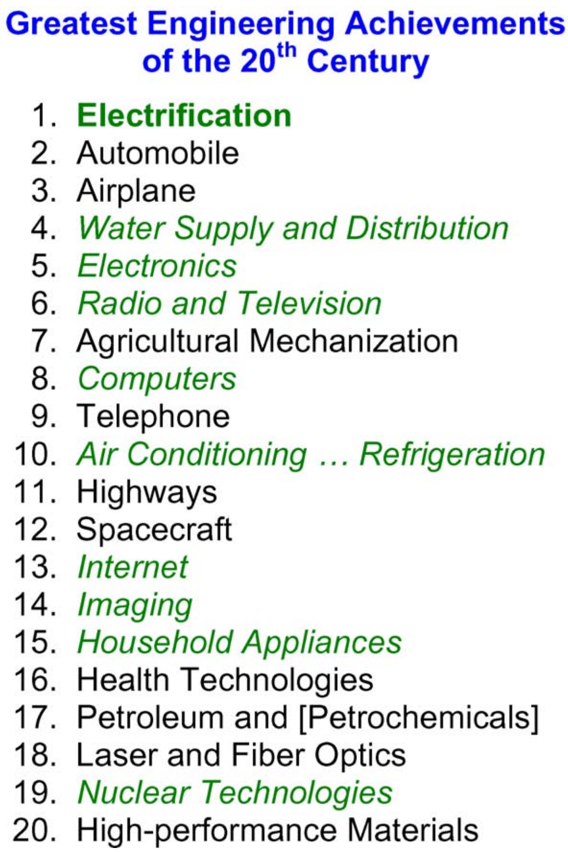

Fig. 1. Greatest engineering achievements of the 20th century. This list, from the U.S. National Academy of Engineering [1], recognizes "Electrification" as Number 1, the achievement of achievements. Subsidiary achievements which scarcely would have been possible without electrification have been italicized.

below 0.5% [18,22]; and one is driven ask whether energetically more productive ways of harnessing the incoming photons might be found. On the up side, dry biomass, albeit fossil, now powers the electric grid; and therefore a (putatively unwise) dependence upon biomass might not require the major efforts which otherwise will be required to store electrical energy in bulk.

2.1.2. Solar heat radiation: Anthropogenic photchemistry

One of the many Grand Challenge problems in science is that of devising an anthropogenic photochemical process which efficiently and robustly converts sunlight and inexhaustible small molecules into fuels. Stated differently, sunlight aided by catalytic metal surfaces drives unfavorable small-molecule activation reactions which culminate in the production of oxygen and a reduced fuel, for example,

$$2H_2O \xrightarrow[PC]{h\nu} 2H_2 + O_2, \qquad (1)$$

where h is Planck's constant, ν is the frequency of the radiation, and 'PC' stands for 'photocatalysis'; the intermediate steps of this reaction generate four electrons and four protons. The heat of formation of gaseous water is 241.8 kJ mol^{-1} implying that, ideally, to extract each mole of gaseous hydrogen, approximately one mole of cyan photons at 500 nm ($h\nu$ = 239 kJ mol^{-1}) must be supplied. Thus, the reaction scheme of Eq. (1) requires managing four electrons, four protons, and the excitations produced by *at least* two photons. At present, small molecule reactions of this complexity are the focus of intense research, and development of the field has reached the point where Nobel Prizes have been awarded, but only for milestones at the one-electron level [23–26]. However, in the laboratory under favorable conditions (and often using exhaustible transition metals) photoefficiencies of H_2 production hover around 1% [23] while the best photon-to-electricity conversions have reached roughly 10% [26]. Such efficiencies are somewhat below those obtained using classical solid-state photovoltaic devices.

2.1.3. Solar heat radiation: Wind energy

Wind energy is at present receiving much attention (e.g., [5,27,28] and has the potential to be a major supplier of grid electricity. However, its utilization is not without potential environmental consequences [29]. And its intermittency is famously unpredictable: "The wind bloweth where it listeth, and thou hearest the sound thereof, but canst not tell whence it cometh, and whither it goeth" [John iii.8]. A significant role for wind energy in a sustainable electric grid most definitely should be undergirded by reliable energy storage.

2.1.4. Solar heat radiation: Rain (hydro) energy

Rain can become a source of energy when it transforms into a stream moving under the influence of gravity. As such, of course, it is just non-tidal non-pumped hydropower. Once a stream is dammed, no additional energy storage is required. However: (i) damming a stream is not entirely without environmental consequences; (ii) such resources must from time to time be refurbished because reservoirs inevitably silt up; and (iii) neither are they as limitless as one might wish, the United States, for example, having a total electric generating capacity of roughly 1,076,000 MW, of which only 77,000 MW are conventional hydroelectric (http://www.eia.doe.gov/cneaf/electricity/epa/epat2p2.html), while perhaps an additional 350,000 MW of conventional hydro capacity could be developed (cf. [30], tab. 9)[4,5]. If strict practices of energy efficiency were to be instituted by the United States, conventional hydropower might be able to supply as much as half of its electrical energy.

2.1.5. Solar heat radiation: Wave energy

Conservatively estimated, the total energy represented by coastal and open ocean waves exceeds 1 TW [31]. At present, however, numerous technical difficulties must be overcome before wave energy converters make a significant contribution to grid energy. And, should they begin to do so, provision for energy storage will be needed since their contribution will be intermittent: because the power in a swell varies roughly as the square of the wave height, it is evident that calm seas yield negligible power.

2.1.6. Solar heat radiation: Photovoltaic converters

A solar cell is a semiconductor device which converts the energy of the incident photons of sunlight into direct current. If this sunlight is taken as the 2000 ASTM Standard Extraterrestrial Spectrum Reference E-490-00 (http://rredc.nrel.gov/solar/standards/am0/ASTM2000.html), there will be worthwhile incident energy at colors (wavelengths) from the UV-C (200 μm) to the mid-infrared (4000 μm). Unfortunately, satisfyingly high conversion efficiencies have thus far been obtained only for monochromatic irradiations, while the sun is a quasi-blackbody. In consequence, realistic efficiencies of mass produced solar cells are at present in the 10–15% range [32]. Even 10% is at least 20-fold

[4] Where appropriate, pointers will be given to page (p.), section (s.), chapter (ch.), equation (eq.), figure (fig.), table (tab.), or experiment (expt.) of the pertinent reference.

[5] In making comparisons among datasets, it is essential to discern the precise nature of the quantities reported. For example, the rated maximum output on a generator nameplate is not the same as the average output as determined annually using a totalizing wattmeter.

Sustainable Energy Sources for the Future

PRIMARY	SECONDARY	TERTIARY	QUATERNARY	QUINTARY
Gravitation				
Earth-Moon	Tides	Grid		
Nuclear				
Natural Terrestrial Fission	Geothermal	Steam	Grid	
Anthropogenic Fusion	Steam	Grid		
Solar Fusion	EM Radiation	Biomass	Steam	Grid
	EM Radiation	Photochemistry	Grid	
	EM Radiation	Terrestrial PV	Grid	
	EM Radiation	Space PV	Microwaves	Grid
	High Temp Solar	Steam	Grid	
	Low Temp Solar	Warm air	Grid	
	Climate	Water (Hydro)	Grid	
	Climate	Waves	Grid	
	Climate	Wind	Grid	

Fig. 2. Classification of the possible sources of sustainable energy.

better than presently obtainable from photosynthesis; and when conversion from biomass to grid electricity is taken into account, photovoltaics probably enjoy a 50:1 efficiency advantage over photosynthesis.

However, earth-based photovoltaic conversion is diurnally intermittent and will require massive energy storage if grid voltage is to be maintained. This would not necessarily be the case (or at least not to the same extent) with space-based solar power [33]. This latter, however, is at present visionary and cannot be counted upon to materialize in the foreseeable future.

2.1.7. Solar heat radiation: High temperature thermal converters

In principle nearly all of the photons impinging upon a plot of land can (with a parabolic reflector) be focussed upon a fluid-filled collector tube whose surface is black over 200–4000 nm and (prospectively) much less emissive above 5000 nm, where radiative heat loss from the tube is expected to be localized; in practice, however, the actual collection efficiency may be closer to 75% [34]. This heated fluid would then be used to develop superheated steam which produces electricity by steam turbine technology. Potentially, this means that one might expect a real thermodynamic turbine efficiency in the mid-30% range and possibly even in the high-40% range (http://en.wikipedia.org/wiki/Fossil_fuel_power_plant), yielding a system efficiency in the high twenties or better and distinctly above that delivered by current photovoltaic devices. Presently, however, there are extant only four commercial installations in the world that are purely solar thermal, although large numbers are under construction or in planning (http://en.wikipedia.org/wiki/List_of_solar_thermal_power_stations).

2.1.8. Solar heat radiation: Low temperature thermal converters.

The low temperature converter most often mentioned is the solar chimney (cf. [35,36], esp. Fig. 1). This device consists of a very high chimney with a wind turbine built into its base; this chimney is surrounded by a low transparent roof which is open at its perimeter and as much as a kilometer in radius. During periods of light, the air under the roof warms, moves radially inwards, and rises up the chimney, thereby spinning the turbine and generating electricity; moreover, generation can be continued into periods of darkness by spreading water filled bags on the ground under the greenhouse roof to make an improved thermal store. There are, however, two shortcomings to the technology. First, the output of collected energy is not readily regulated on demand, and agile external storage will desirable. Second, the theoretical maximum energy efficiency of such a system, from incident sunlight to joules delivered to the power grid, is on the order of 3% or less (e.g., [37,38]). The largest prototype unit ever built [35] had a theoretical maximum efficiency of 0.64% and was rated at 50 kW; its predicted monthly output agreed with the output determined under test ([39], Fig. 12).

2.2. Deep terrestrial fission reactions

2.2.1. Deep terrestrial nuclear processes: Geothermal energy

Geothermal resources can be viewed in several ways, of which the most important is the expected steady flux of heat energy upwards from the Earth's core. Roughly 99% of the Earth's surface lies in the range of 0–200 $mW\,m^{-2}$ with an average of perhaps 50 $mW\,m^{-2}$ ([40], ch. 2); over the remainder of the surface the average might be on the order of 1 $W\,m^{-2}$ with rare hot spots exceeding 1000 $W\,m^{-2}$. To put this into perspective, the annual average insolation over the United States exceeds 100 $W\,m^{-2}$ (http://mapserve2.nrel.gov/website/L48NEWPVWATTS/viewer.htm). Thus, in the steady state the geothermal resource is less than 0.1% of the solar resource, suggesting that – except in niche applications – it will be unimportant in a sustainable energy future.

Nevertheless, underlying many regions of the world, there are large deposits of heated water at depths less than a few kilometers [40,41], and these could be tapped for process heat. These, presumably, are depletable deposits, and once exhausted can be refilled only by slow thermal diffusion.

Finally, there are rare geothermal fields where the heat fluxes are unusually high and steam powered electric generation is feasible, but where there is no sure way of predicting how long the local magmatic conditions which power them will perdure (cf. [42]; http://en.wikipedia.org/wiki/Geothermal_power#United_States). Moreover, such plants may often be treated as base load generating facilities and as such might profitably be combined with efficient bulk storage of their output megajoules.

It is of interest to note that, over the decade 1995–2005, world geothermal generating capacity grew only at the modest rate of 240 $MW\,year^{-1}$ [42].

2.3. Human mediated nuclear reactions

2.3.1. Human-mediated nuclear reactions: Controlled fission

Fission reactors produce heat which is employed to produce steam that in turn spins a turbine generator and produces

electricity. Delays in making major output adjustments in a coal fired plant are normally a few hours or less (cf. [43], p. 2.1–7; Schainker [60]); whereas a nuclear power plant is rather less output-agile, and the response time can become days ([43], p. 2.1–7). Thus, a grid powered by them should be amply supplemented with agile energy storage.

Fission has severe drawbacks in any scenario of long-term energy sustainability. First, notwithstanding 50 years of investigation, the key problem of radioactive waste disposal has not yet been resolved [44–46]; and we know of no convincing argument that it can ever be resolved in practice. Nevertheless, the supply of fissile isotopes seems, even with increased usage, to be adequate for at least a century and to offer a viable short-term solution if one is willing to risk the environmental consequences (e.g., [47]). Second, even with breeder technology, the supply of fissile material seems adequate only for a millennium or so because an atom once split is not recyclable. Thus, as a long-term energy source, nuclear fission is neither sustainable nor "green".

2.3.2. Human-mediated nuclear reactions: Controlled fusion

Proof-of-feasibility for envisioned commercially viable fusion power reactors has not yet been demonstrated [48]. The magnitude of their radioactive waste problems is predicted to be much less than that from fission reactors [48,49]; however, even though the neutron irradiation of lighter nuclei tends to yield isotopes of shorter half life than the neutron bombardment and fission of heavy isotopes, this does not necessarily imply that waste storage will be trivial.

Naturally, the ultimate output-agility of fusion reactors is unknown; but since their heat to electricity process contains a steam generation step, we presume that, in analogy with large coal-fired installations and conventional nuclear power plants, both physics and economics will impose incentives for steady-output operation with slow ramp times. If so, massive capabilities for the bulk storage of grid power will again be desirable.

2.4. The need for energy storage

The upshot of Sections 2.1–2.3 is that, ultimately, a preponderance of humanity could well be left dependent upon a restricted set of primary sources for supplying electric energy to the grid, among which the most prominent are: (i) wind turbines; (ii) earth-based solar power (both photovoltaic and high-temperature solar thermal); (iii) space-based solar photovoltaic power; and (iv) nuclear fusion. The last two are speculative. The first two, in one form or another, seem eminently feasible. But they are INTERMITTENT ! And they can undergird an infinite-busbar power grid only in conjunction with massive bulk storage of energy.

Whether, because of sources which lack output agility or sources which are intermittent, it appears that the electricity grid of a sustainable-energy future will need a huge capability to store energy if it is efficiently to match consumer demand with generator supply.

3. Storage of electrical energy in massive quantities

It became abundantly clear in the previous sections that an infinite-busbar electric grid powered by renewable sustainable energy must make provision for load balancing by incorporating ample means of energy storage. Fortunately, many strategies exist for doing this, and each is characterized by at least four "soft" characteristics of great importance:

(a) Robustness. Because the grid and its energy reservoirs undergird our modern world, this system must have the resilience of an anvil. "Resilience of an anvil" is a fuzzy concept and not readily quantifiable: different people will interpret the term in different ways. But virtually everyone will get the idea that the system must be so sturdy that only a remarkably catastrophic event could ever take it down.

(b) Longevity. Think Roman aqueduct!

(c) Greenness. No artifact of mega-engineering, which is what we are talking about here, is without side effects. But it would be nice if energy storage facilities aged gracefully and neither degraded into high tech badlands nor failed catastrophically. And it would be a big plus if they generated negligible malign waste during operation.

(d) Simplicity of maintenance. This has two faces: first, the actual physical process of maintenance must be easily mastered and readily accomplished; and, second, *independent* at-a-glance verification of that maintenance must be possible.

These four must then be supplemented by four potentially quantifiable figures of merit:

(e) Cycle efficiency = (total joules of electricity reverted to the infinite busbar from the store)/(total joules of electricity delivered to the store). Over the length T of a single simple cycle, first of charging and then of discharging, this can be idealized as

$$\eta = -\int_{t_c}^{T} p(t)\mathrm{d}t \Big/ \int_{0}^{t_c} p(t)\mathrm{d}t, \qquad (2)$$

where η is the efficiency, t is the time, $p(t)$ is the instantaneous power (assumed positive during charging of the store and negative during reversion), and t_c is the crossover time between charging and reversion. Obviously, the maximum allowed value of $\int_0^{t_c} p(t)\mathrm{d}t$ for a particular storage reservoir is one possible definition of the *reservoir capacity C*. More generally, the efficiency relation can be expressed as

$$\eta = \int_{0}^{T} [H(p) - 1]\, p(t)\mathrm{d}t \Big/ \int_{0}^{T} H(p)\, p(t)\mathrm{d}t, \qquad (3)$$

where $H(p) = 0$ for $p(t) \leqq 0$ and $H(p) = 1$ for $p(t) > 0$ and where T is a significant time span such as an entire diurnal cycle or a month or a year. Cycle efficiency is a property of the entire storage *system*. Since that system is usually a concatenation of many subsystems each of which has its own efficiency $1 > \eta_j > 0$ ($j = 1, 2, \ldots, J > 1$), it follows that

$$\eta = \prod_{j=1}^{J} \eta_j. \qquad (4)$$

The practical lesson of this equation is that getting a 30 cycle efficiency requires meticulous attention to *every* subsystem because for *every* value of j it is the case that $\eta < \eta_j$.

(f) Volumetric energy density D of a reservoir, here defined as

$$\mathcal{D} = \mathcal{C}/\mathcal{V}, \qquad (5)$$

where $\mathcal{C}$ is energy density and $\mathcal{V}$ is the rated geometric volume (footprint) of the reservoir.

(g) Limiting normalized drawdown rate δ. Let $\mathcal{P}_{\max}$ be the maximum recommended power flow between the reservoir and the grid, where $\mathcal{P}_{\max}$ need not necessarily be the same charging the reservoir as discharging it. Then $\delta = \mathcal{P}_{\max}/\mathcal{C}$.

(h) Response time τ of an energy reservoir. At the present development of storage technologies, this figure need not be terribly precise but should be within a factor of two of the time required for $p(t)$ to achieve roughly 90% of its recommended maximum level following receipt of a deliver-power command. The value of τ need not necessarily be the same charging as discharging.

Table 1
The seven commonly cited *systems* with potential for bulk storage of electrical energy and nine criteria for describing them. The provenance for the table entries is generally given in the Appendix or derives from manufacturers' literature.

Mode	Criterion								
	(a) Robustness	(b) Longevity	(c) Greenness	(d) Simplicity	(e) Cycle efficiency (dimensionless)	(f) Energy density ($MJ\,m^{-3}$)	(g) Max. drawdown (s^{-1})	(h) Response time (s)	(i) Acceptance
(i) Underground pumped hydro	Potentially outstanding	Potentially high	Potentially high	Extreme	~80%	$\gtrsim 5$	$\sim 4.0 \times 10^{-6}$	$\lesssim 15$	Unproven but very attractive
(ii) AA-CAES	Untested	Potentially high	Potentially medium	Unknown	Potentially $\lesssim 65\%$	$\gtrsim 100$	$\sim 35 \times 10^{-6}$ (8 h discharge)	Potentially $\lesssim 15$	Unproven and perhaps pricey
(iii) Battery	Potentially fair	Battery life 2 years	Medium if recycled	Potentially medium	$\lesssim 70\%$	$\lesssim 1500$	$\sim 0.3 \times 10^{-3}$ (1 h drawdown)	$\lesssim 0.1$	Mature technology, but pricey
(iv) Fuel cell	Potentially medium	Unknown	Potentially good	Potentially medium	$\lesssim 50\%$	NA	NA	$\lesssim 15$	Experimental but attractive
(v) Kinetic energy	Potentially good	Design life 20 years	Very	Potentially medium	~ 80%	$\gtrsim 45$	~8	$\lesssim 0.1$	Pricey but in production
(vi) SMES	Potentially fair	Potentially medium	Very	Potentially medium	Potentially ~80%	~40	Unknown, but of order 1	$\lesssim 0.1$	Currently not in production
(vii) Ultra-capacitor	Potentially fair	Potentially medium	Very	Potentially medium	Potentially ~80%	$\gtrsim 25$	~1	$\lesssim 0.1$	Pricey but in production

Finally, we should specify, at least qualitatively, some measure of economic and/or societal merit for the technology:

(i) We have elected *not* to specify a single quantifiable economic figure of merit because this would be so dependent upon unpredictable regulatory constraints, unexpected developments in technology, unappreciated externalities, unknowable market size, and unstandardized constraints upon construction of the economic model. We shall instead give a pithy but subjective qualitative assessment.

Thus, in selecting a particular system for bulk storage of grid energy, one is working with at least a nine-dimensional objective function for each system considered.

For bulk storage of momentarily surplus grid electricity, which has already been generated by an arbitrary mixture of processes, there exist only a few methods of "parking" the energy until it is needed. These have been reviewed extensively (e.g., [11,13,50–60], [61] s. 16.3, [62–64]),[6] so extensively as to obscure the potentially simple underlying issues. Fundamentally, one can bleed electrical energy from an ac power line, sometimes rectify it, and ultimately store it:

(i) As gravitational potential energy in a pumped hydraulic scheme.
(ii) As a compressed gas.[7]
(iii) As electrochemical energy in a battery.
(iv) As chemical energy in the feedstock of a fuel cell.
(v) As kinetic energy in a flywheel.
(vi) As the magnetic field energy of an inductor.
(vii) As the electric field energy of a capacitor.

Other serious contenders may ultimately evolve; but for the moment no others come to mind, and these seven have been the principle ones for a long, long time.

These 7 storage technologies and 9 criteria are explored, respectively, in the 7 rows and 9 columns of Table 1, whose 63 data entries are derived and discussed in the Appendix to this paper. To qualitatively winnow these 7 candidate technologies for a particular application, it is necessary only to prepare a rough utility matrix for the 9 criteria and apply it to Table 1.[8]

For use with the electricity grid to store huge quantities of energy for diurnal (and longer) supply–demand matching, it would seem that, barring yet-to-occur technological breakthroughs, only (underground) pumped hydro and compressed air energy storage merit serious further consideration and that the former is the front runner.

4. Discussion

In this review, we have focussed upon the bulk storage of electrical energy to maintain the infinite busbar convenience of the electricity grid, as we have come to know it. But there is no obvious reason why distributed storage cannot, for niche applications, also be used both efficaciously and extensively. For example, thermal-offset for residential comfort heating can be stored in a large insulated water tank and topped up by electrically powered heat pumps during periods of grid energy abundance. For example, motive power for one's car can be stored in batteries. And consumers can be encouraged to do precisely this by pricing electricity lower during times of plenty.

The take home lesson from Table 1 appears to be that, using technology which is either extant or realistically foreseeable, the cycle efficiency of the bulk storage of grid energy should be greatest using pumped hydro; and this is independent of the price of the electricity itself. Similarly, a recent economic analysis of battery vs. flywheel vs. pumped hydro storage reveals that present day costs of flywheel or battery storage are at least thrice that of pumped hydro [65]. The magnitude of pumped hydro's economic advantage may drop with technical developments in alternative storage technologies; and the difficulty of computing future energy costs is notoriously tricky [66]. But, because of pumped hydro's cycle efficiency, its attractiveness may actually increase with rising energy costs.

[6] Attention is called also to the websites of the Electricity Storage Association http://electricitystorage.org/ and the Energy Storage Council http://www.energystoragecouncil.org/. Additionally, a report entitled Challenges of Electricity Storage Technolgies was issued in 2007 by the American Physical Society http://www.aps.org/policy/reports/popa-reports/upload/Energy-2007-Report-ElectricityStorageReport.pdf.

[7] It is worth noting that this energy is not "elastic" in the common physical sense of the term which connotes atoms held together by spring-like binding forces. In a gas, ideally, the gas particles interact only kinetically by collisions.

[8] In contemplating such a utility matrix, there may be a temptation to look back fondly upon a "paradigm" chemical storage medium such as iso-octane (2,2,4-trimethyl pentane). This compound has a specific gravity of 0.892 and a heat of combustion of 44.4 $MJ\,kg^{-1}$. Its energy density is thus 39.6 $GJ\,m^{-3}$, which upon combustion should yield at least 13 $GJ\,m^{-3}$ of electrical energy. This is a gold standard against which other methods of energy storage could usefully be measured.

Pumped storage is already used for "peak shaving" by meeting transient periods of high demand through injection into the grid of energy taken from the grid during periods of low demand during which it was deemed uneconomic simply to turn off some generators. For example, typical delays to bring a power plant online after 8 h of shutdown might be (cf. [43], p. 2.1–7): pumped storage, 3 min; oil, 3 h; liquefied natural gas, 3 h; coal, 4 h; nuclear, 5 days. This huge comparative advantage in agility, coupled with the gigawatt level powers available, make pumped storage extremely attractive. In today's market, peak-load electric power may, per GWh wholesale, command $100,000 (http://www.eia.doe.gov/cneaf/electricity/wholesale/wholesale.html); to a utility, this could make a strategy of nibbling away at the losses in present or planned pumped storage schemes look extremely attractive.

For buffering an electricity grid with energy efficient stores of GWd magnitude, the only obvious rival to pumped hydro appears to be advanced-adiabatic compressed-air energy storage using an underground cavern to hold the compressed air (e.g., [50,67,68]). AA-CAES has the putative advantages (i) of higher energy density storage, and (ii) of being readily locatable almost anywhere and not just where there are highlands for a reservoir. Recent analysis, however, suggests that the former advantage comes with the downsides (a) of rather more complex and costly equipment and (b) of reduced cycle efficiency [69]. However, the latter advantage appears less notable when it is recognized that pumped hydro presumably can also be located most places simply by boring a lower reservoir several hundred meters below ground surface and using the rubble from the boring to construct an upper reservoir on the surface.

An informed decision between AA-CAES and underground pumped hydro cannot be made on the basis of extant practical experience because neither of the two schemes has ever, to our knowledge, been actualized on a GWd scale. Considering the transcendent societal importance of making the switch to sustainable energy smooth, sure, and swift, this is unfortunate for our species. We suggest that, despite the tendency in recent decades to slight energy research [70,71], a reasonable path to comparative evaluation of the two (and/or others which might by breakthrough be devised) would be (A) to form a consortium of nations with resources, (B) to establish performance specifications and constraints for GWd storage facilities, (C) to encourage each member nation forthwith to construct (using suppliers from within its borders) at least one AA-CAES facility and one underground pumped hydro facility, and (D) to evaluate openly all results using the same protocol.[9] Robust energy storage should be treated not as an issue of competitive advantage among nations, but rather as a cooperative endeavor for the well-being of global humanity.

[9] This proposed activity is clearly a megaproject beyond the scale of the Large Hadron Collider at CERN or the International Thermonuclear Experimental Reactor at Cadarache, France. So it may justly be asked why the storage issue should not likewise be subjected to modeling studies for a decade or so to divine the best pathway forward. The answer is that, like the United States' development of the atomic bomb during World War II, we do not have the time. Humanity is about to embark upon a roller coaster ride down the far side of Hubbert's Peak and we need by 2020 a massive infrastructure actively constructing sustainable energy generation buffered by large-scale energy storage. The leisure to proceed sedately has already been squandered by mankind, as for example by the United States' disinvestment in energy research over the past generation [70,71]. At this present moment, the optimism attributed to communities of experts (e.g. [66]) should be disregarded and humanity should proceed wastefully with multiple independent trials of GWd storage facilities. At worst we will end up with a few suboptimal facilities plus a lot of practical experience in what not to do. The United States in World War II, not knowing in advance the best path to uranium enrichment, opted for three somewhat different enrichment programs in parallel, only one of which (gaseous diffusion) is still in general use today (http://www.fas.org/nuke/intro/nuke/uranium.htm). But it got the job done. And it is precisely this sort of urgency that large scale grid buffering needs in order to become a commercial reality.

Appendix. Candidate technologies for grid energy storage

A.1. Preliminaries

For each of the seven technologies described below it must be borne in mind that no suitable technology has been identified for directly accumulating the 50- or 60-Hz electrical energy coursing through the grid and then feeding it back as needed. This can be done only indirectly, and often with considerable loss. First, there must be an input Energy Conversion Module (ECM_{in}) which takes the high voltage ac and converts it into a conveniently storable form. Then there must be an Energy Storage Module (ESM) which actually warehouses the converted energy. Finally, there must be an output Energy Conversion Module (ECM_{out}) which turns the storable form back into high voltage ac.

A.2. Underground pumped hydro

"Pumped hydro" or "hydroelectric pumped storage" of electrical energy refers to a scheme in which surplus electric power is used to pump water vertically upwards (ECM_{in}) by an altitude h from a lower reservoir to an upper reservoir (ESM), where it is held until there is a deficit of electrical power. Water from the upper reservoir is then run downwards through a turbine (ECM_{out}) to the lower reservoir, thereby converting its gravitational potential energy into grid power. The energy density per meter of elevation of the elevated water is simply (density of water) $\times$ (acceleration of gravity) which at 20 °C and standard acceleration of free fall is 9789 J m^{-4}. As the single-stage lift capacity of commonly employed Francis-type turbine is now about 650 m (e.g., [72]), this implies an energy density of about 6.4 MJ m^{-3} $\doteq$ 1.8 kWh m^{-3} stored in the water of the upper reservoir. Translated to the scale of bulk storage, a lossless system of this head would require approximately 14×10^6 m^3 to store an entire gigawattday (1 GWd = 86.4 TJ); or a reservoir 1000 m $\times$ 1000 m $\times$ 50 m would suffice to store approximately 3.7 GWd. It should be noted in connection with the above example that, throughout discharge of the reservoir, the effective head would remain approximately constant in the range 650 $\pm$ 25 m; thus, unlike many other modes of storage, the recoverable energy content of the ESM (reservoir) does not vary drastically with the discharge rate; neither is there a notable sag in power output as the ESM empties, nor is it necessary to retain a "reserve" or "cushion" in the ESM.

Such pumped storage schemes with both reservoirs *above* ground are numerous and their technology well developed (e.g., [43,73,74]), although few such facilities have been built within the United States in recent decades. Surprisingly, to our knowledge, no major scheme with one reservoir deep underground has ever been constructed; and why we cannot with certainty say. Certainly the idea has been discussed for many years (e.g., [75–77]). Clearly it possesses the signal advantage that such construction is not topographically restricted to sites where above ground upper and lower reservoirs can be placed close together, because, in principle, a *lower* reservoir can be bored out of bedrock almost anywhere and the spoil distributed on the surface immediately above it to form an upper reservoir. Moreover, a study commissioned by the Electric Power Research Institute (Palo Alto, CA, USA) found no insurmountable technical impediments to such a development [78]; but it did recommend focussed development efforts to (i) identify suitable siting opportunities in the USA, (ii) examine potential environmental impacts, (iii) engineer more robust hoists for raising and lowering heavy equipment, (iv) produce pump-turbines with progressively higher head ranges (ultimately approaching 1000 m), and (v) advance the technology of underground excavation. More recent geotechnical examination of the concept has likewise identified no daunting barriers to such energy storage [79]. We therefore surmise that the added costs associated

with excavating the lower reservoir may have sufficed to render the technology uneconomic within the recent economic zeitgeist.

Prospectively, since this technology is hydraulic, we anticipate extreme robustness, longevity in excess of half a century, great simplicity, and little pollution beyond that associated with the source of the electrical energy stored. Cycle efficiencies as high as 80% are already attainable (cf. [43]) and can presumably be pushed gradually higher by nibbling away at the various sources of loss; for example, maximum generator efficiency under optimal operating conditions, which was $\sim$92% in the early 1990s, rose[10] to 97.7% with the powering up of Unit No. 1 of the Kannagawa project in 1995 (cf. [72,80]). Moreover, a pump-turbine can go from on-line to full-load in 15 s or less ([43], p. 1–5).

As an illustration, the Kannagawa scheme with only Unit No. 1 generating, $\mathcal{P}_{\max} = 482$ MW and C = (reservoir volume) $\times$ (energy density) = $(19.2 \times 10^6) \times (6.3 \times 10^6) = 121 \times 10^{12}$ J implying $\delta = 4.0 \times 10^{-6}$; when all six units are on-line this scheme will be able to run at full rated power for about 10 h.

A.3. Advanced-adiabatic compressed-air energy storage (AA-CAES)

This technology would employ grid energy to adiabatically compress air that would then be pumped into an underground cavern for storage; and, when the grid needed additional energy the air would then be run through a turbine to spin a generator and provide that energy (e.g., [50,68,69,81]). This we have discussed it in detail elsewhere [69], where we concluded that it was technically feasible but: (i) that to procure heat exchangers of adequate effectiveness would be both expensive and difficult; (ii) that the required compressor and expander trains would be expensive and possibly of lower than desirable efficiency; (iii) that AA-CAES was untested; and (iv) that in an era of expensive energy, cycle efficiency would assume much greater importance, thereby making it difficult for AA-CAES to compete with pumped hydro.

A.4. Batteries

Batteries store energy as electrochemical potential between two electrodes and are classified as either primary (not normally rechargeable) or secondary (rechargeable). Secondary batteries have properties that make them highly attractive for power grid applications: rechargeability, modular configuration, rapid response time, moderate energy density, and the ability to absorb or deliver appreciable power [82–85]. Many chemical combinations exist for secondary batteries, too many to review here; but the current leading candidates for a sustainable energy future are (i) lead-acid because of its reassuringly mature technology and (ii) lithium ion because of its efficiency and volumetric energy density [84,86]. (A case could perhaps be made for flow batteries; but, as they use two liquid electrolytes, they are somewhat similar to fuel cells, which have been selected instead for discussion (Section A5).)

Lead-acid batteries have been a standby in industry for well over a century and are manufactured in wide variety to meet specialized needs [84]; and significant improvements are still occurring, the energy density having risen by about one-half in the last 50 years [86]. Today, for example, the Absolyte 1-100G99 (Exide Technologies, Büdingen, Germany), employed for photovoltaic and alternative energy technologies, has a nominal energy density of 290 MJ m^{-3}. However, cycle life of lead-acid batteries remains between 50 and 2000 cycles, with the shorter lifetimes being associated with deeper discharges [84]. Its self-discharge varies widely depending upon electrode construction and storage temperature; however, it need not exceed 0.1% per day and should be a quite minor contributor to the cycle efficiency [84].

The lithium-ion battery, first commercialized by Sony in 1990, has saturated the portable electronics market but has only recently become popular as a candidate for bulk energy storage. Its specific energies (both mass and volumetric) are much better than lead-acid's, as is its cycle life; and it self-discharges only 1% per month [86]. Unlike the lead-acid battery, lithium-ion is not a mature technology; and new options for anodes and cathodes are constantly being sought (e.g., organosulfur compounds [87]; silicon nanowires [88]; http://news-service.stanford.edu/news/2008/january9/nanowire-010908.html]; and nanoscale $FeSn_2$ [89]) in hope that lithium-ion battery systems can be made more cost competitive. The biggest energy storage applications at present envisioned for lithium-ion battery technology are the laptop computer (http://www.boston-power.com) and the all-electric automobile (http://www.a123systems.com). Both applications are in states of rapid technological evolution; and both specifications and technical details are often closely held. However, the small (1.95 Ah) Panasonic CGA103450A is rated at over 500 cycles, has an energy density (when new) of 1.4 GJ m^{-3}, and can be had off the shelf at $13 each in small quantities – thus leading to an anticipated cost of perhaps 0.5 M$ m^{-3}.

It must be emphasized that a battery system for storing grid energy consists of far more than just an array of batteries. One must also provide a not inexpensive balance of plant (BOP), which includes both (i) electronic interfacing between grid and battery and (ii) HVAC to assure a salubrious operating environment [90].

More precisely, in order to store grid energy in batteries (or fuel cells, or flywheels, or superconducting inductors, or ultracapacitors) it is necessary first to convert the ac to dc by a process of rectification and regulation (ECM_{in}), both portions of which have losses. Similarly, going the other way, the dc voltage of the batteries must be passed through a synchronous inverter and fed back into the power grid (ECM_{out}). We admit that high voltage direct current technology converts reliably from ac to dc to ac at voltages above 100 kV and does so with losses under 2% ([91], s. 32.5.8). Electrochemical cells, however, normally have voltages under 5 V, which could require the individuals cells to be arranged in multi-kilocell, series-connected stacks, even though such a strategy is known to undercharge or overcharge many individual cells, waste energy, and degrade battery life (e.g., [92]). At the other extreme, high voltage step-down and step-up transformers could be employed so that the charging can be handled in few-cell modules; and, fortunately, such transformers are low loss and can have efficiencies in excess of 99% ([93], pp. 2–7). However, breaking the ac-to-dc conversion step down into industrial size modules of a few tens of volts and only kilowatt charging rates leads to manufacturers' data sheet values of only 85–90% for the rectification and regulation step executed electronically (e.g., http://www.lambdapower.com/products/hws-series.htm); interestingly, the efficiency of present day chargers appears to be rather lower than this [94]. Going the other way, data sheet values for solid state inverters encourage one to hope for efficiencies on the order of 85% (e.g., http://www.theinverterstore.com/the-inverter-store-product.php?model=pwrig300012s-top-250#).

Hence, exclusive of losses within the ESM (i.e., the batteries themselves), the round-trip efficiency should not be significantly less than 70% when a solid-state conversion route is taken. The ECM_{in} and ECM_{out} considerations for batteries are generally believed qualitatively similar to those for flywheels (e.g., [95], p. 7) and by extension should obtain also for fuel cells, superconducting magnetic energy storage systems and ultracapacitors.

The efficiency with which the electric energy received at the terminals of a lead-acid battery can be recovered upon discharge is

[10] We thank the Corporate Communications Department of The Tokyo Electric Power Company for providing efficiency data on Unit No. 1 of the Kannagawa project.

termed the turnaround (or charge/discharge) efficiency; and this is commonly quoted as 75–80% ([84], p. 23.1). Thus, optimistically, a ballpark estimate of cycle efficiency for this type of battery could be in the 60% range. The turnaround efficiency of Li-ion batteries is somewhat higher, being 95–98% ([84], p. 35.47). Our hunch is that this figure-of-merit has never been systematically optimized for any type of battery operated for grid storage and subjected to a somewhat predictable charge/discharge cycle.

The experience of many electrical engineers in an undergraduate electrical machines laboratory might lead one to wonder whether rotary converters or dc-machine/synchronous-machine couples might not offer possible alternatives for conversion. However, the empirical reality of the past 50 years is that the power industry has shifted steadily from rotary converters to electronic ones, presumably because the latter are more efficient.

A.5. Fuel cells

A fuel cell is an energy conversion device that produces electricity as a byproduct of a chemical reaction between exogenously supplied reactants, normally hydrogen and oxygen. Fuel cells are different from electrochemical cell batteries in that they consume reactant in an open system, whereas batteries store electrical energy chemically in a closed system. In addition, a fuel cell's electrodes are catalytic and relatively stable; by contrast, the electrodes within a battery react and change as a battery is charged or discharged.

Many different types of fuel cells have been investigated and developed since the early 1900s [96,97]. Fuel cells are usually classified according to the type of electrolyte used in the cells or the temperature ranges during the operations. Listed below is a brief summary of major fuel cell types.

(a) High temperature operating range (above 100 °C) fuel cells include:
- Phosphoric acid fuel cells (PAFC) use liquid phosphoric acid as an electrolyte and porous carbon electrodes containing a platinum catalyst. PAFCs are less powerful and more expensive than other fuel cells.
- Solid oxide fuel cells (SOFC) use a hard, non-porous ceramic compound as the electrolyte. SOFCs are expected to be around 50–60% efficient at converting fuel to electricity. SOFCs operate at very high temperatures – around 1000 °C.
- Molten carbonate fuel cells (MCFC) use an electrolyte composed of a molten carbonate salt mixture suspended in a porous, chemically inert ceramic lithium aluminum oxide ($LiAlO_2$) matrix.

For high temperature operating fuel cells, non-precious metals can be used as catalysts at the anode and cathode, reducing operation costs. The primary disadvantage of high temperature fuel cells is their durability. High temperature in a fuel cell usually leads to slow startup and requires significant thermal shielding to retain heat and protect the system. The high operating temperatures also impose constraints on material selections.

(b) Low to medium temperature operating range fuel cells include:
- Direct methanol fuel cells (DMFC) are powered by pure methanol operating under 20–90 °C, which is mixed with steam and fed directly to the fuel cell anode. This technology is more recent and methanol has a higher energy density than that of hydrogen.
- Alkaline fuel cells (AFC) use a solution of potassium hydroxide in water as the electrolyte and can use some cheap metals as a catalyst at the anode and cathode. AFCs' performance can be hindered by the presence of carbon dioxide (CO_2). The purification of hydrogen and oxygen adds extra cost to the system.
- The proton exchange membrane (PEM) fuel cell (also known as polymer electrolyte membrane fuel cell, PEMFC) has been studied more extensively than the other fuel cell technologies because they have the most potential to be applied for power generation, storage and portable power applications. Due to the low operating temperatures of PEMFCs the only emissions produced are water vapor and heat.

A PEMFC consists of a solid polymeric proton conducting membrane that is sandwiched between two porous platinum-catalyzed gas-diffusion electrodes in a single cell. Due to recent advances in perfluorosulfonic acid membranes, typified by Nafion [98], the power density of PEMFC can reach 4 kW m^{-2}, possess fast startup time (maximum power to the load within 20 ms), and can last over 100,000 h at the single cell level, thus outperforming other fuel cell types. In particular, PEM fuel cells are suitable for use in large scale energy storage applications due to their low sensitivity to orientation, and favorable power-to-weight; but it should be pointed out that platinum is geochemically rare and should be considered exhaustible.

The ECM_{in} for a polymer electrolyte membrane fuel cell system begins with a voltage step-down and rectification step (as with a battery) but follows this with a water electrolysis step where additional loss is incurred because commercial electrolyzers presently operate with efficiencies around 80% (e.g., [99]), although experimental electrolyzers have reached 95% under laboratory conditions [100]. The ESM step can be simple storage of hydrogen gas, which itself is energetically lossless; however, compression and/or liquefaction and/or transportation each can introduce significant reductions in the cycle efficiency. Finally, the ECM_{out} step ends with a dc-to-ac conversion (as in a battery) but begins with an imperfect transformation of chemical energy to electrical energy in a hydrogen/oxygen fuel cell of theoretical maximum efficiency not greater than 83% ([96], eq. 2–17). In practice the output voltage of a fuel cell varies with ambient temperature hydrogen pressure and output current, with a rule of thumb being that from no load to full load the output voltage will drop about 20% ([96], Fig. 3–7); the implication of this is that the output efficiency can be further degraded by as much as 20%. If, for purposes of illustration, we optimistically take the input ac-dc conversion efficiency as 92%, the electrolyzer efficiency as 85%, the hydrogen transportation/storage efficiency as 95%, the fuel cell efficiency as $83\% \times 0.9 = 75\%$, and the output dc-ac conversion efficiency as 92%, then the overall cycle efficiency will not exceed 51%. We note that the energy conversion efficiency of a PEMFC is higher than that which would be obtained by combusting the hydrogen to run a turbine generator because the latter is a heat engine and therefore Carnot limited, while the former transformation proceeds directly from the chemical energy of the hydrogen to electrical energy without a thermal intermediate step. That is, the fuel cell, as a chemical process, can have a maximum theoretical efficiency higher than either Carnot cycle or Otto cycle thermal efficiency [101].

The disadvantage of a PEMFC is its slow reaction rate at low temperature. This shortcoming needs to be compensated by adding catalysts to separate the hydrogen's electrons and protons. This step usually adds cost for the fuel cell system. Furthermore, degradation can occur by slow oxidation of the proton conducting membrane at the anode/membrane and cathode/membrane interfaces by free radical oxygen species. The reported price for plug power 5-kW power plant at a US army research center, stationary PEM fuel cells, and PEMFC powered vehicles is around \$1000–2000/kW (see: http://www.hydrogen.energy.gov/pdfs/review05/fc48_stone.pdf).

A.6. Flywheels

A flywheel is a weighty structure, cylindrically symmetric about a revolving shaft, which serves either to regulate machinery or to accumulate energy for subsequent use. The potter's wheel is a paradigm. In the present scenario: an ECM_{in} transforms grid ac into a form suitable for driving a motor which accelerates a high velocity rotor (flywheel) made of a modern composite; this flywheel is the ESM and stores rotational kinetic energy; finally, an ECM_{out} turns the kinetic energy back into grid ac (cf. [102]).

As a potential strategy for coping with diurnal demand fluctuations of electric power systems it goes back at least 60 years [103]. The first instance we found in which a flywheel was actually used to sustain the power quality of a system of significant size dated from the 1950s [104]: to operate the magnet of the Cosmotron particle accelerator at Brookhaven National Laboratory (Upton, NY, USA) required each minute 12 sub-second pulses of 26 MW peak magnitude and would have gravely disturbed the power grid of eastern Long Island; the problem was resolved with a 43-ton steel-plate flywheel, rotating at 892 rpm (no load) and having a typical stored energy of 110 MJ, which held the power peaks on the input line to under 2 MVA.

The present state of flywheel technology/research has recently been reviewed by Bolund et al. [102]. In particular, they can be switched from discharging to charging in less than 0.1 s [105].

What actually can be obtained "off the shelf" (*sensu lato*) is illustrated by the Smart Energy Matrix 20 MW Frequency Regulation Plant (Beacon Power, Tyngsboro, MA, USA) which is an aggregation of 200 independent flywheel modules, each rated to hold 90 MJ in a spindle rotating on magnetic-levitation bearings within a vacuum; the flywheel is approximately 2 m high by 1 m in diameter, yielding an energy density in the spindle in excess of 45 MJ m^{-3}. Energy losses expected are on the order of 10% associated with ECM_{in} and spin-up, 10% associated with ECM_{out} and spin-down, and 2%/h of rated energy content during steady state rotation[11] ([106], p. 10). The nominal price of a single 90-MJ flywheel module is in the 150–175 k$ range.

A.7. Superconducting magnetic energy storage (SMES)

The basis of this device is that the act of establishing a current within a wire requires energy which is stored in the magnetic field set up by that current. When the electromotive force which established the current is suitably turned off, it is normal for the current to run down gradually as the stored energy is dissipated by ohmic loss in the wire and the magnetic field decays. The lure of superconducting storage is that energy stored in the magnetic field need not be dissipated ineffectually because superconducting wire has no ohmic loss. An informative introduction is provided by the review article of Luongo [107]; and a more recent topical review has been given by Xue et al. [108]. An ECM_{in} rectifies grid ac into a dc voltage that elevates the current within a superconducting inductor that constitutes the ESM, thereby storing the input power in the inductor's magnetic field. Ultimately, an ECM_{out} draws down the inductor current, back-converting the field energy into power grid ac.

The energy density of a magnetic field under non-superconducting circumstances is well known to be (e.g., [109], ch. 4)

$$\mathcal{D}_{\text{magnetic}} = \frac{1}{2}\mu H^2 = \frac{1/2B^2}{\mu},$$

where μ is the permeability of the storage medium (normally close to that of free space, $\mu_0 = 4\pi \times 10^{-7} H\,m^{-1}$); B is the magnetic flux density and H is the strength of the magnetic field, and both increase with current. However, the current cannot be increased indefinitely because for each superconducting material there is a maximum value (the critical current) beyond which its superconductivity is quenched. Nevertheless, flux densities on the order of 10 T have been achieved at 4.2 K (e.g., [110]), pointing toward potentially achievable energy densities on order of 40 MJ m^{-3}. Experimentally, achieved energy densities have already reached perhaps one-third of this [110]. Such energy densities far exceed those of a classic iron-core filter choke such as the Essex-Stancor model C-2692 of 1977 which achieved roughly 2.4 kJ m^{-3}.

The maximum rated output power depends upon the voltage rating of the superconducting inductor and is not a figure commonly quoted. Let I_{max} be the rated current and V_{max} the rated voltage. Then $\delta = \mathcal{P}_{max}/\mathcal{E}_{max} \leqq V_{max}I_{max}/\mathcal{E}_{max}$. Suppose that $\mathcal{E}_{max} = 5.0$ MJ, $I_{max} = 1$ kA, and $V_{max} = 1$ kV; then $\delta = 0.2$.

Despite several decades of interest in SMES and a relatively vibrant literature, commercialized systems have been few in number. For example, in 1983, a 30-MJ helium-cooled SMES coil was brought online in the electrical grid of the Bonneville Power Administration to enhance system stability and operated successfully for some months [111]; it is no longer in service, and today only a heavy concrete foundation block remains. For example, in approximately 1999 American Superconductor manufactured for the Wisconsin Public Service Corporation six low temperature superconducting storage modules, each with 3-MJ capacity and response time on the order of milliseconds and a price of two-thirds of a million dollars [112]; as of 2008, all six units were still in operation. However, SMES is not at present successfully extending its market penetration.

Our sense is that the system stability issues on power grids have come to be adequately handled by advances in power electronics while SMES storage of bulk power probably has been deferred pending developments in the area of high temperature superconductive materials sufficient to enable robust and cost effective coil operation at 77 K (cf. [113]).

A.8. Ultracapacitors

Ultracapacitors bear little superficial resemblance to a classical capacitor such as the prototypic Leyden jar. Nevertheless, both store charge; and their stored energy is associated with the electric field established by that charge. The difference between them is that a classical capacitor stores its charge on sheets of metal foil separated by a thin dielectric membrane whereas the ultracapacitor does it by attracting solvated ions to a conducting surface using electric fields too low to pull the ions out of their solvation shells (e.g., [114,115]). The practical difference is that the energy density has risen from about 4.5 kJ m^{-3} for a low voltage aluminum electrolytic capacitor of the mid-1970s (Cornell-Dubilier FAH 1000000-3-D9) to roughly 25 MJ m^{-3} for the 2008 Nesscap ESHSP-3500C0-002R7-ND (3500 F) ultracapacitor. Ultracapacitors are not cheap; and a cubic meter of such capacitors presently costs upwards of 200,000 $US. However, this stored energy is available in milliseconds or less and could be useful for power quality applications, if not for bulk storage of grid energy.

In an ultracapacitor *system*, power electronics ECM_{in} transforms the ac into a form suitable for charging a multi-capacitor array of ultracapacitors (the ESM); and ultimately a power electronics ECM_{out} turns the energy held by the ESM back into grid ac. However, the working voltage of an ultracapacitor is less than 3 V. This is much less than the hundreds of kilovolts at which a grid operates, raises all of the issues of inverter technology already discussed for batteries (q.v.), and suggests (optimistically): (i) that electronic conversion efficiencies in the 70% range will have to be borne to effect the transition, first from grid to storage and then

[11] This loss during steady state rotation bears comparison with the roughly 5–10%/min which can be estimated for the Cosmotron flywheel [104].

from storage to grid; and (ii) that considerable care must be taken to assure that individual capacitors not be pushed into overload by stochastic property variations of their neighbors in the array.

The maximum energy density to be anticipated from this technology can be estimated as follows. Consider a parallel plate capacitor of plate area A, plate spacing d, permittivity ε, and plate voltage V. Then, following standard classical electromagnetics (e.g., [109], ch. 2), the stored energy will be $(^1/_2\varepsilon A/d)V^2 = {}^1/_2\varepsilon\mathcal{V}E^2$, where the electric field is $E = V/d$. Next, let $\varepsilon = \varepsilon_0$, where Δ is called the dielectric constant and $\varepsilon_0 \sim 10^{-9}/36\pi$ is the permittivity of vacuum. Thus

$$\mathcal{D}_{\text{electric}} = {}^1/_2\Delta\varepsilon_0 E^2$$

The limit to energy density in this model is the breakdown electric field E_b of the dielectric. For the special case in which the dielectric is vacuum and the dielectric constant unity, the failure phenomenon is known as "vacuum breakdown", the breakdown is highly dependent on the fabrication of the electrodes, and $E_b \lesssim 10^{10}$ even in the best of circumstances [116]; if, in recognition of the unacceptability of breakdown in an ultracapacitor installation, one allows a safety factor of $10^{1/2}$ in the breakdown voltage, $\mathcal{D} \lesssim 50 \times 10^6$ for vacuum. In non-vacuum breakdown, limiting field strengths are typically on the order of 10^8 V m^{-1}, being $\sim 150 \times 10^6$ for n-alkanes (cf. [117]) and $\sim 200 \times 10^6$ for diamond (cf. [118]) to give (with a safety factor) $E_b{}^2 \lesssim 10^{16}$; hence, maximum energy densities for an aqueous dielectric with its high dielectric constant are $\mathcal{D} \lesssim 5 \times 10^6$. That is, the present energy density of an ultracapacitor is already a notable achievement and one should not look forward with confidence to vast future improvements.

To the first order, an ultracapacitor at low frequency operation can, in the same fashion as a classical capacitor, be represented in terms of ideal capacitance shunted by a parallel admittance, the pair being in series with a small series impedance (cf. [115], ch. 15; [119]). For bulk energy storage, the series impedance can usually be neglected the parallel admittance represented as a simple parallel conductance. For example, calculations based upon 2008 data sheets of the Nesscap Co. (http://www.nesscap.com/products_lineup.htm) show that each farad of ultracapacitance will have associated with it a parallel conductance on the order of 0.5–1.0 μS. That is, realistically, an ultracapacitor could lose to leakage 10–20% of its stored energy over a 24-h period. If, however, great power is needed quickly, then the maximum allowed current becomes limiting and this is on the order of 0.5–1.0 A F^{-1}; hence the drawdown is on the order of 1 s^{-1}.

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